DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CITY OF TUCSON

HYDROLOGIC INVESTIGATIONS
ATLAS HA–713 (SHEET 1 OF 3)

EXPLANATION

Qf **Fort Lowell Formation**—Gravel to clayey silt; also includes thin surficial alluvial deposits of late Pleistocene and Holocene age — Pleistocene — QUATERNARY

Unconformity

Ts **Tinaja beds, undifferentiated**—Gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. Includes tuff beds and interbedded volcanic flows

Tsu **Upper Tinaja beds**—Gravel to clayey silt

Unconformity

Tsm **Middle Tinaja beds**—Gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. Queried where uncertain

Unconformity

Tsl **Lower Tinaja beds**—Gravel and conglomerate to clayey silt and mudstone. Queried where uncertain — Miocene and Pliocene — TERTIARY

Unconformity

Tos **Pantano Formation**—Conglomerate, sandstone, mudstone, and gypsiferous mudstone. Includes megabreccia, tuff beds, and interbedded volcanic flows. Queried where uncertain — Oligocene

Unconformity

Volcanic rocks, undifferentiated, v—Flows, necks, dikes, and plugs. Tuff, welded tuff, agglomerate, and breccia; basaltic andesite to rhyolite; includes some interbedded conglomerate, sandstone, and siltstone

Sedimentary rocks undifferentiated, sr—Conglomerate, sandstone, mudstone, shale and quartzite, some limestone interbedded volcanic flows, tuffs, and agglomeratic tuff

Granitic rocks, undifferentiated, g—Granite, quartz monzonite, granodiorite, dioritic monzonite, and quartz latite porphyry. Includes granitic gneiss and schist — PRECAMBRIAN TO TERTIARY

v sr g

Contact

Concealed fault—Approximately located. U, upthrown side; D, downthrown side. Queried where uncertain

Line of geohydrologic section—Dot is well along section line; letter and number, *B1*, are geohydrologic section and sequence of well in section. Larger dot is vertical extensometer installation; dashed line is projection of well to section

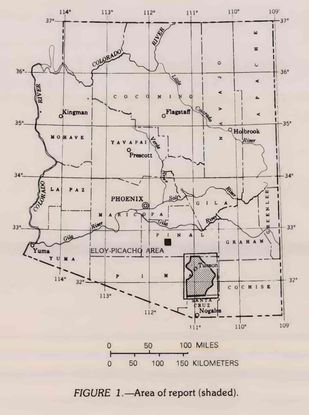
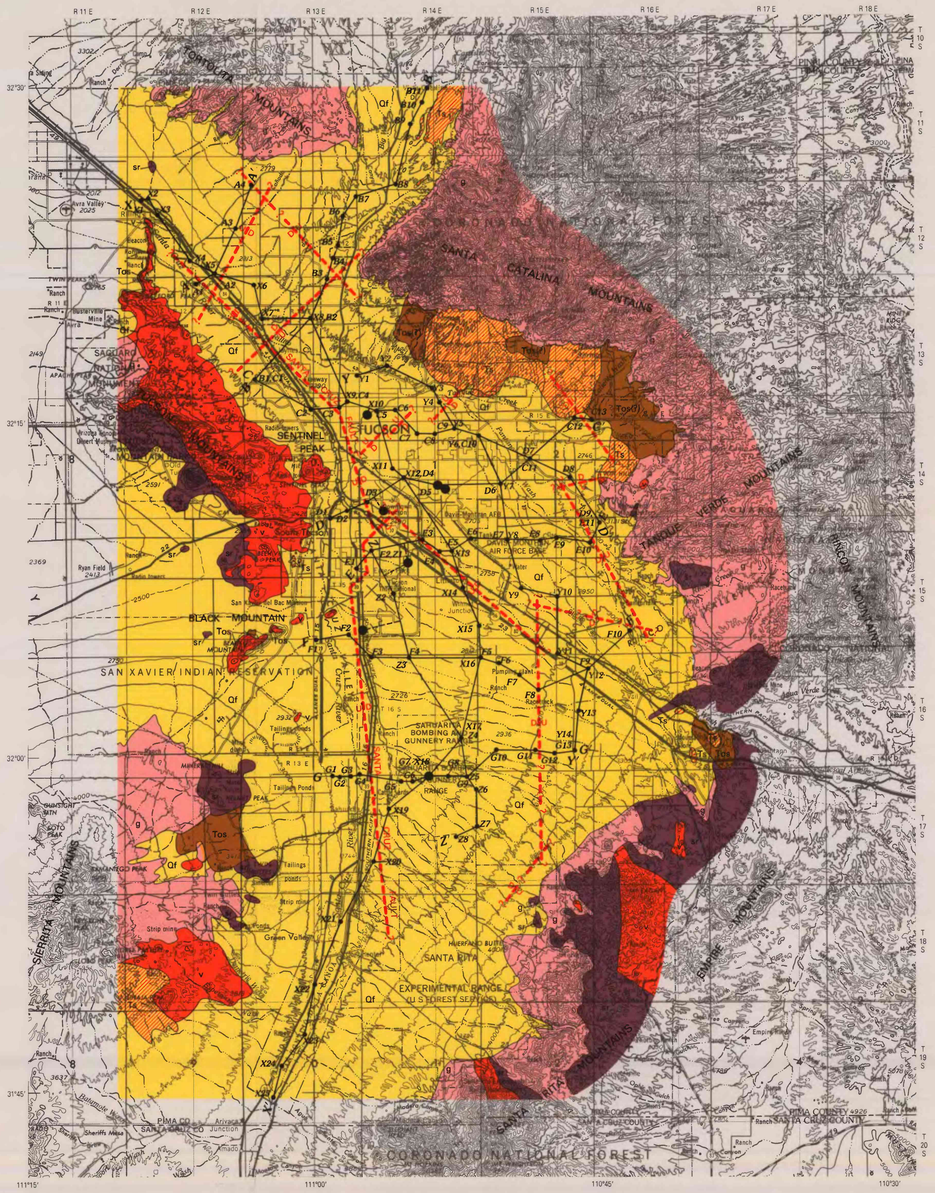


FIGURE 1.—Area of report (shaded).



Base from U.S. Geological Survey 1:250,000 Nogales, 1956-69 and Tucson, 1956-77

Geology modified from Laney (1972) and Davidson (1973)

FIGURE 2.—Generalized distribution of rock types in the Tucson basin.

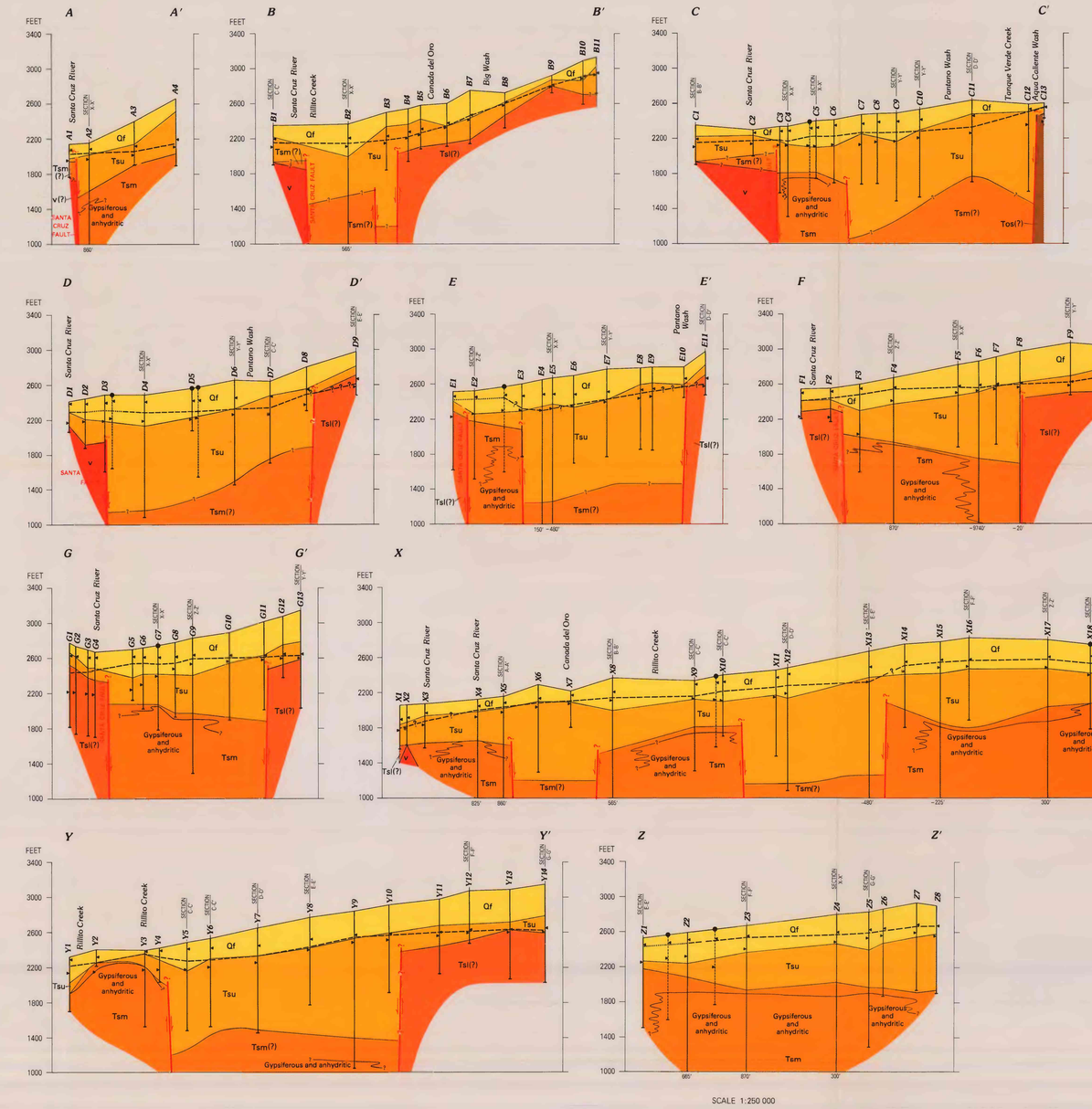


FIGURE 3.—Geohydrologic sections in the Tucson basin.

EXPLANATION

Qf Fort Lowell Formation
Tsu Upper Tinaja beds
Tsm Middle Tinaja beds
Tsl Lower Tinaja beds
Tos Pantano Formation
v Volcanic rocks, undifferentiated

Gypsiferous and anhydritic clayey silt and mudstone unit—Approximately located. Queried where uncertain

Contact—Approximately located. Queried where uncertain

Fault—Approximately located. Queried where uncertain. Arrows show relative movement

Well—Dashed where projected to sections. Letter and number, **D6**, are geohydrologic section and sequence of well in section. Dot is vertical extensometer installation. Figure, 870′, is altitude of bottom of well above NGVD of 1929 for wells deeper than sections. Figure, −225′, is altitude of bottom of well below NGVD of 1929 for wells deeper than sections

D6 870′ −225′

Water level in well

Measured or approximated in 1940

Measured or approximated in 1981. Dotted line is zone of suspected perched ground water.

Estimated 2030 water level

CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

INTRODUCTION

The Tucson basin is a large north- to northwest-trending alluvial basin in Pima County, Arizona (fig. 1). The 1,000-square-mile basin is bounded on the north, east, and west by steep mountains that rise abruptly above a broad and gently sloping valley floor. The climate of the valley is semiarid, and the average annual precipitation is about 11 in. (Sellers and Hill, 1974). Three major ephemeral streams—the Santa Cruz River, Rillito Creek, and Pantano Wash—drain the area. These streams and their tributaries provide a source of recharge to an extensive alluvial aquifer that underlies the valley floor. The aquifer consists of interbedded gravel, sand, silt, and clay and contains a vast amount of ground water.

The physiography, fertile soil, and mild climate of the Tucson basin make it an ideal environment for agriculture and urban development. The city of Tucson, which occupies a large area of the basin, is a major and rapidly expanding urban center. Demand for water for irrigation, public supply, and industry is high. Streamflow is intermittent and generally of short duration and therefore is not a dependable source of water. Ground water pumped from the aquifer is the main source of water in the valley. Although the aquifer is recharged by natural infiltration and underflow, the rate of recharge has not kept pace with the rate of pumping. Pumping has exceeded recharge for several decades, and declines in ground-water levels have occurred in parts of the basin. In places, water-level declines have resulted in small amounts of aquifer compaction and land subsidence.

Aquifer compaction, land subsidence, and earth fissures can severely damage or affect the functional capability of manmade features. Aquifer compaction may damage wells, differential land subsidence may adversely affect structures such as sewers and irrigation water-supply systems that are dependent on gravity for their operation, and fissures may damage engineered structures. In addition, compaction and subsidence can seriously reduce the ground-water storage capacity of the aquifer, and fissures may provide a direct path for the rapid movement of contaminants from the land surface to the aquifer.

Damage that results from compaction, subsidence, and fissuring has occurred in the Eloy-Picacho area (fig. 1)—about 50 mi northwest of the study area (Schumann and Poland, 1970; Davidson, 1973; Laney and others, 1978). Hundreds of square miles in and near the Eloy-Picacho area have been affected by compaction, subsidence, and fissures induced by ground-water withdrawal. Survey data indicate that 120 mi^2 subsided about 7 to 12.5 ft from 1952 to 1977. Many earth fissures have opened in this area; the fissures are commonly more than 1,000 ft long and generally surround areas of large water-level decline and subsidence. The potential for related damage in the Tucson basin has been suggested by Platt (1963) and Davidson (1973).

In 1979 the U.S. Geological Survey, in cooperation with the city of Tucson, began an investigation of aquifer compaction and the effects of land subsidence and earth fissuring in the Tucson basin. The primary purposes of the investigation are to monitor the amounts of aquifer compaction and land subsidence and to define areas of related potential hazards. This report describes geohydrologic characteristics of the Tucson basin that may contribute to potential aquifer compaction, land subsidence, and earth fissures.

The quantitative evaluation of potential land subsidence in this report is presented as an interim land- and water-use planning tool pending acquisition and study of additional data. Cautious interpretation of the results is necessary because only a small amount of compaction and subsidence had occurred in the Tucson basin as of 1985. Because of data limitations, the evaluation was made on the assumption that future compaction and subsidence in the Tucson basin will be similar to that in the Eloy-Picacho area. The assumption also was made that ground-water withdrawals from the basin would continue at the 1970–78 rates. Although the continuation of withdrawals is probable, several factors may lessen the overdraft of the aquifer and thus the potential magnitude of land subsidence. The factors include the enactment of the 1980 Arizona Ground-Water Management Act, the planned importation of Colorado River water by the Central Arizona Project, the increased effluent reuse and reclamation, and the probable long-term decrease in pumping by agricultural and some industrial users.

Stratigraphic and structural relations presented in this report are based, in part, on local and regional data that were unavailable during a previous study of the Tucson basin by Davidson (1973) and represent a revision of his interpretation. The geologic discussion, therefore, is intended as an extension of the discussion by Davidson (1973). Some of the stratigraphic and structural relations in this report, which were used to evaluate potential land subsidence and earth fissures, can be interpreted in other ways. Alternative geologic interpretations, however, should have little if any impact on the evaluation because the stratigraphic and structural boundaries presented in this report correspond with the lithologic changes in the sediments of the aquifer that are most likely to affect the magnitude and extent of compaction.

During this investigation, cooperation was received from many employees of the city of Tucson. The author would like to thank R. Bruce Johnson, Chief Hydrologist; Joseph A. Babcock; Gary L. Hix; Gerald J. Huerstal; and Lynn Brumbaugh of the Tucson Water Planning Division and Don H. Madsen, Administrator; Daniel J. Sweet; and Melvin S. Sanderson of the Tucson Water/Water Resources Division. The author is also especially grateful to Herbert H. Schumann, B. L. Wallace, Colleen A. Babcock, and Melinda K. Cuff of the U.S. Geological Survey for their advice and support.

GEOHYDROLOGIC SETTING

The mountains surrounding the Tucson basin consist of igneous, metamorphic, and indurated sedimentary rocks of Precambrian to Tertiary age (fig. 2) that generally yield only small to moderate amounts of water to wells and springs along the margins of the basin. Withdrawal of water from the rocks of the mountains probably will result in little or no compaction. The valley floor is underlain by unconsolidated to indurated sedimentary deposits of Tertiary and Quaternary age (figs. 2 and 3) that yield small to large amounts of water to wells within the basin. Withdrawal of water from some of these deposits may result in moderate to large amounts of aquifer compaction.

Major sedimentary units in the Tucson basin are the Pantano Formation of Oligocene age, the Tinaja beds (informal usage) of Miocene and Pliocene age, and the Fort Lowell Formation of Pleistocene age (Davidson, 1973). The Pantano Formation consists of conglomerate, sandstone, mudstone, and gypsiferous mudstone. The Tinaja beds consist of deposits ranging from gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. The Fort Lowell Formation is made up of gravel, sand, and clayey silt.

An evaluation of the rock units and geologic structures in relation to the hydrology of the basin was made by Davidson (1973). Analyses of drill-hole and geophysical data during this study have resulted in modifications of some of Davidson's interpretations. Three modifications that have relevance to this report are the subdivision of the Tinaja beds into three units, the relocation of a major probable fault in the east-central part of the basin, and the reversal in throw of a major probable fault in the central part of the basin. These and other geologic relations in the subsurface may greatly affect the potential for aquifer compaction, land subsidence, and earth fissures in the basin.

The Tinaja beds are comprised of three unconformable units (figs. 2 and 3). Davidson (1973, p. 20–21) recognized, but did not map, lower and upper units of the Tinaja beds. A third unit of intermediate age, the middle Tinaja beds, is recognized in this report on the basis of ages of volcanic rocks at depth within the central part of the basin (Eberly and Stanley, 1978; Scarborough and Peirce, 1978). The Tinaja beds are interpreted as a sedimentary detrital filling of a subsiding structural basin (Davidson, 1973). Sediments of the Tinaja beds generally are coarse grained along the margins of the basin and grade into finer grained and evaporitic deposits in the central downfaulted parts of the basin. The middle and upper Tinaja beds were deposited in response to block faulting during the Basin and Range disturbance. Sediments of the middle Tinaja beds lie mainly in the central downthrown structural block, which is bounded by the Santa Cruz fault and the subparallel fault system adjacent to the Tortolita, Santa Catalina, Tanque Verde, and Santa Rita Mountains (figs. 2 and 3). As mapped in this report, the lower Tinaja beds include many subsurface deposits along the edges of the basin that were previously assigned by Davidson (1973) to the Pantano Formation. The middle Tinaja beds include some sedimentary sequences in the central parts of the basin that were previously assigned by Davidson (1973) to the Pantano Formation and lower Tinaja beds. The upper Tinaja beds as mapped here include the uppermost sediments of Tertiary age in the basin.

Davidson (1973) indicated that in the Sierrita Mountains (fig. 2), the lower part of the Tinaja beds includes basaltic andesite and dacitic volcanic rocks that are of probable late Tertiary age—Miocene(?), or 26 to 12 m.y. (million years old). Similar flows on Black Mountain and Sentinel Peak (fig. 2) range in age from about 26 to 19 m.y.; those of Black Mountain overlie the Pantano Formation (Davidson, 1973). A well drilled on the upthrown side of the Santa Cruz fault in sec. 35, T. 15 S., R. 13 E., east of Black Mountain near wells *F1* and *F2* (figs. 2 and 3, section *F-F′*) penetrated a sequence of basaltic andesite flows between 600 and 800 ft below the land surface. The flows east of Black Mountain, which range in age from 27.0 to 24.9 m.y. (Paul Damon, University of Arizona, written commun., 1986), are overlain by indurated sediments of probable lower Tinaja age. Farther to the east on the downthrown side of the Santa Cruz fault in well *F6* (figs. 2 and 3, section *F-F′*), sedimentary and volcanic sequences that correlate with the Pantano Formation, the volcanic flows of Black Mountain, and the lower Tinaja beds are buried by thousands of feet of younger basin fill of the middle and upper Tinaja beds and Fort Lowell Formation. The middle Tinaja beds penetrated by well *F6* overlie volcanic rocks that range in age from 23.4 to 11.6 m.y. (Eberly and Stanley, 1978; Scarborough and Peirce, 1978).

On the basis of their relation to volcanic rocks in and adjacent to the basin, the lower Tinaja beds are early to mid-Miocene and perhaps late Oligocene in age. On the basis of their relation to the dated sequence of volcanic rocks in well *F6*, the middle Tinaja beds are younger than 12 m.y., and are probably middle to late Miocene in age. The upper beds are Pliocene and perhaps late Miocene in age, but the suggestion of this age is permitted only by regional correlation with sediment of similar structural involvement and stratigraphic position (Davidson, 1973). These criteria and correlation of the upper Tinaja beds to a dated sequence of upper basin fill in the adjacent Sonoita Creek area (Menges and McFadden, 1981), indicate that the upper beds may range in age from about 5.8 to 2.0 m.y.

The lower Tinaja beds are hundreds to thousands of feet thick and consist of gravel and conglomerate to clayey silt and mudstone (figs. 2 and 3). The middle Tinaja beds are hundreds to thousands of feet thick and consist of gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. The upper Tinaja beds are hundreds of feet thick and are made up of gravel, sand, and clayey silt. Where penetrated by wells, the lower Tinaja beds consist mainly of silty gravel and conglomerate and the sediments of the middle beds consist primarily of gypsiferous and anhydritic clayey silt and mudstone. Subsurface deposits of the upper Tinaja beds consist mainly of sand and clayey silt in the central part of the basin and gravel and sand adjacent to the mountains.

Data from well cuttings, cores, and geophysical logs indicate that sediments of the upper Tinaja beds probably are more likely to compress due to the effects of ground-water withdrawal than the higher density and more cemented deposits of the lower and middle Tinaja beds. The geometry of the subsurface contacts between the lower, middle, and upper Tinaja beds (fig. 3) therefore is of great importance in the evaluation of potential land subsidence hazards in the basin. The contact between the upper and middle beds generally is distinguishable in wells; however, the contact between the upper and lower beds is, in places, difficult to detect.

In the northern part of the basin where the upper Tinaja beds are coarser grained than the middle Tinaja beds, the contact between the units generally is characterized by an abrupt downward increase in clay content accompanied by a change from gray or grayish-brown detritus to reddish-brown sediment. In the southern part of the basin where both units consist mainly of fine-grained deposits, the contact between the upper and middle beds generally is characterized by a downward change in sediment color from brown to reddish brown throughout the interior of the basin. In the contact is typically underlain by gypsiferous and anhydritic clayey silt and mudstone that causes a distinctive change in the signatures of a variety of geophysical logs. The upper beds do not contain evaporites.

The contact between the upper and lower Tinaja beds is difficult to detect in wells because of the coarse-grained nature of the deposits and the general absence of unique and readily identifiable lithologic features. The contact is generally characterized by a downward increase in sediment density and cementation accompanied, in places, by changes in sediment color, size, sorting, angularity, and (or) mineralogy. In some areas west of the Santa Cruz fault and in the Canada del Oro Valley (fig. 2), the contact is characterized by an abrupt downward increase in calcium carbonate content as indicated by the reaction of cuttings to dilute hydrochloric acid. In parts of the Canada del Oro Valley, the increase in calcium carbonate content below the contact is accompanied by a change in mineralogy from gneissic-rich clasts to granitic detritus.

The structural interpretations in this report are based, in part, on the subsurface relations between the lower, middle, and upper Tinaja beds, and differ from earlier structural interpretations presented by Davidson (1973). A major northeast-trending probable fault was mapped by Davidson (1973, pl. 1) that extended from sec. 4, T. 13 S., R. 13 E., to sec. 2, T. 17 S., R. 14 E., in the east-central part of the basin. The fault, which was interpreted as bounding part of the central downfaulted block of fine-grained and evaporitic deposits, is, in this report, relocated farther to the east along a north-south trend (fig. 2). The relocated fault is based on drill-hole and gravity data that indicate probable vertical offset between the lower and middle Tinaja beds adjacent to a steep north-trending gravity gradient east of the earlier mapped fault (figs. 2 and 3, sections *F-F′*, *G-G′*, and *Y-Y′*) (Davidson, 1973). Wells *F6*, *F8*, and *G10*, which lie on the downthrown side of the relocated fault, penetrate sediments of the middle Tinaja beds at depths ranging from 960 to 1,280 ft. Wells *Y11*, *F9–Y12*, *F10*, *Y13*, *G12*, and *Y14–G13*, which lie on the upthrown side of the fault, penetrate sediments of probable lower Tinaja age at depths ranging from 470 to 570 ft.

Davidson (1973, pl. 1) also mapped a major northwest-trending probable fault in the central part of the basin approximately parallel to Interstate 10. The fault was interpreted by Davidson as being downthrown toward the southwest and a probable structural boundary between sediments of Pantano and Tinaja age. On the basis of revised stratigraphic correlations, the fault is reinterpreted as being downthrown toward the northeast and a probable structural boundary between sediments of middle and upper Tinaja age. If the interpretation in this report is correct, the middle Tinaja beds, which are generally more cemented and composed of higher density materials than the overlying upper beds, are offset by more than 800 ft across the fault (figs. 2 and 3, sections *E-E′* and *X-X′*). Regardless of the structural interpretation, the upper 1,000 ft of saturated sediments that lie northeast of the fault appear more likely to compress from the effects of ground-water withdrawal than the equivalent thickness of sediments that lie southwest of the fault.

The Pantano Formation, lower Tinaja beds, and middle Tinaja beds consist largely of moderately indurated to indurated deposits that may be generally resistant to deformation related to ground-water withdrawal. These deposits may, in places, be susceptible to compaction; however, their lithologic properties indicate that they are far less prone to compaction than the overlying deposits of the upper Tinaja beds and Fort Lowell Formation. The upper Tinaja beds and Fort Lowell Formation consist largely of unconsolidated to poorly indurated deposits that may, in places, be greatly susceptible to compaction where saturated. The potential for aquifer compaction and its effects in the basin, therefore, is dependent mainly on the characteristics of the upper Tinaja beds and Fort Lowell Formation and the relation between these units and bedrock. As used here, bedrock includes the rocks of the mountains and the deposits of the Pantano Formation, lower Tinaja beds, and middle Tinaja beds.

The aquifer consists of the Pantano Formation, the Tinaja beds, and the Fort Lowell Formation (Davidson, 1973) as shown in figure 3. The Pantano Formation yields small to moderate amounts of water to wells, and the Tinaja beds yield small to large amounts of water to wells. The Fort Lowell Formation is the most permeable unit in the aquifer and yields moderate to large amounts of water to wells (Davidson, 1973). Coarse-grained deposits of the upper Tinaja beds and Fort Lowell Formation commonly yield more than 1,000 gal/min of water to properly constructed wells.

Water stored in the coarse-grained parts of the aquifer near the edges of the basin occurs under unconfined or water-table conditions. Aquifer tests indicate that water stored in the Pantano Formation is under leaky confined conditions where it is overlain by or contains fine-grained sediments (Davidson, 1973). Anomalously shallow ground-water levels and (or) cascading water in some wells indicate that perched ground water may lie above the regional water table in parts of the basin (figs. 3 and 7) (Babcock and others, 1982). The zone of suspected perched ground water northeast of Black Mountain occurs where the saturated deposits of the upper Tinaja beds and Fort Lowell Formation consist largely of fine-grained sediments. Fine-grained sediments of the upper Tinaja beds and Fort Lowell Formation in the central and southern parts of the basin contain a large percentage of the volume of water that is stored in the aquifer. Because the sediments generally are more compressible than their coarse-grained counterparts elsewhere in the basin, the potential for aquifer compaction in these areas is high.

The potential for aquifer compaction in the Tucson basin is greatly dependent on the thickness and clay-silt content of the saturated sediments of the upper Tinaja beds and Fort Lowell Formation. Major variations in thickness of the upper Tinaja beds that are related to the structural deformation of underlying bedrock may profoundly affect the amount of compaction and subsidence and the formation of fissures in parts of the basin as water-level declines (fig. 3). Potential effects of these variations may be greatest in areas where the upper Tinaja beds are also rich in clay and silt. Areal distributions of clay- and silt-size particles—diameters of less than 0.0625 mm—contained in the upper Tinaja beds and Fort Lowell Formation are shown in figures 4 and 5 (see sheet 2). Montmorillonite clay is the dominant interstitial clay in the Tucson basin (Laney, 1972) and a major constituent of the fine-grained sediments. Overall, montmorillonite probably accounts for 90 to 95 percent of clay minerals in the sediments on the basis of local and regional sampling (F.N. Robertson, Hydrologist, U.S. Geological Survey, oral commun., 1984). Montmorillonite clay is more compressible than other clay minerals and more susceptible to compaction (Meade, 1968). The percentage of clay and silt in well cuttings, by weight, was averaged over the thickness of the formation penetrated by each sampled well (figs. 4 and 5). Well cuttings generally were sampled every 5 to 10 ft of well depth. Most wells fully penetrate the Fort Lowell Formation; however, many wells only partially penetrate the upper Tinaja beds. In the central parts of the Tucson basin, the sediments of the upper Tinaja beds and Fort Lowell Formation are about 500 to 1,000 ft thick (fig. 3). Sediments of these units consist of 40 to more than 80 percent clay and silt in about a quarter of the basin (figs. 4 and 5). The potential for aquifer compaction and land subsidence is greatest where the saturated deposits of these units are both thick and rich in clay and silt.

The potential for localized differential land subsidence and earth fissures is greatest where saturated fine-grained deposits of the upper Tinaja beds and Fort Lowell Formation overlie shallowly buried faults or convex irregularities in the bedrock (figs. 2–5). The potential also may be great where the saturated sediments of the upper Tinaja beds and Fort Lowell Formation change abruptly from mainly coarse grained to fine grained in composition across a short distance in the aquifer (figs. 3–5). The compressibility of the deposits, amount and distribution of ground-water pumpage, and resultant water-level declines will ultimately control the magnitude and extent of these effects in the basin.

EXPLANATION OF TERMS AND PROCESSES

In this report, an *aquifer* is defined as a body of sedimentary materials that is sufficiently permeable to conduct ground water and to yield economically significant quantities of water to wells and springs (Meinzer, 1923). *Aquifer compaction* is the decrease in thickness of an aquifer that is caused by the withdrawal of water and resultant reduction in size of intergranular spaces within compressible aquifer deposits (Poland and Davis, 1969). Aquifer compaction results in *land subsidence*, which is the sinking or settlement of the land surface (Poland and others, 1972). Unequal sinking or settlement of the land surface between adjacent areas is called *differential land subsidence* and may be localized or regional in nature. *Earth fissures* are narrow, vertical tensional breaks that form in alluvial deposits: those that form as a result of localized differential land subsidence are sometimes referred to as *subsidence fissures* (Schumann and Poland, 1970; Jachens and Holzer, 1979). Subsidence fissures that show vertical offset have been referred to as *faults* (Jachens and Holzer, 1979). Fissures that are eroded by flowing water form wide gully-like depressions called *fissure gullies* (Kam, 1965).

Unconsolidated to poorly indurated sediments undergo compaction as a result of a variety of natural phenomena. *Natural compaction* results mainly from the weight of overlying sediments; however, other natural phenomena that press on or shake the sediments, such as earth tides and occasional stress from seismic activity, may also cause compaction. Natural compaction of such sedimentary materials is greatly accelerated by the withdrawal of ground water. The lowering of the ground-water table or a decrease in artesian head results in the rearrangement and closer packing of the coarse and essentially incompressible aquifer grains and the compression and partial dewatering of compressible fine-grained aquifer materials (Davidson, 1973). An aquifer is most susceptible to compaction where it is rich in clay but permeable enough so that substantial amounts of water can be withdrawn (Davidson, 1973).

Aquifer compaction consists of *elastic* and *inelastic components* (Poland and others, 1972). The elastic component is recoverable and results in aquifer expansion when a rise in water level or an increase in artesian head occurs. The inelastic component is nonrecoverable and results in permanent compaction of the aquifer. In clay and silt-rich—fine-grained—aquifer materials, the inelastic component commonly is many times larger than the elastic component. In sand and gravel-rich—coarse-grained—materials, however, the inelastic component may be small compared to the elastic component. The elastic component occurs simultaneously with water-level decline, whereas the inelastic component may occur at a slow rate (Poland and others, 1972). Maximum compaction of an aquifer may lag the water-level decline or decrease in artesian head by as much as several years (Helm, 1978). The time lag is caused by slow drainage of water from fine- to coarse-grained beds. The nature of the time lag is dependent on clay-bed thickness, permeability, and pore pressure.

Compaction of aquifer deposits occurs when the upward pressure or buoyancy of the ground-water reservoir is reduced as a result of a decrease in artesian head or a decline in water level. A reduction of upward pressure or buoyancy increases the *vertical effective stress* exerted on the aquifer deposits. The resulting compaction is dependent on the *preconsolidation stress*, which is the maximum vertical effective stress to which the aquifer sediments have been previously subjected (Casagrande, 1936; Holzer, 1981). Water-level decline will be accompanied by elastic compaction if the resulting increase of vertical effective stress is less than the preconsolidation stress. Elastic compaction occurs in the preconsolidation range but may include a small inelastic component (Poland and others, 1972; Holzer, 1981). Water-level declines will be accompanied by *virgin compaction* if the resulting increase of vertical effective stress is greater than the preconsolidation stress. Virgin compaction consists of elastic and inelastic components (Poland and others, 1972). The inelastic component of virgin compaction typically is much larger than the elastic component, especially if the aquifer is rich in clay and silt. In general, virgin compaction causes a much greater magnitude of volumetric strain in the aquifer than does elastic compaction and, therefore, may be much more damaging.

The magnitude of water-level decline that is necessary to initially induce virgin compaction of aquifer materials has a wide range and is related, in part, to the degree to which the materials are naturally consolidated in relation to overburden pressure. A lowering of the water level or a decrease in artesian head may soon lead to virgin compaction in normally consolidated aquifer materials. Commonly, however, aquifer sediments are naturally overconsolidated and compact elastically until tens or hundreds of feet of water-level decline have occurred. *Overconsolidation* is defined as the consolidation of sedimentary material greater than that normal for the existing overburden (Bates and Jackson, 1980). The magnitude of the water-level decline where compaction of overconsolidated aquifer materials initially changes from elastic to virgin in nature is referred to in this report as the *threshold water-level decline* (Holzer, 1981).

Specific unit compaction, *aquifer compaction per unit of water-level decline*, and *land subsidence per unit of water-level decline* are useful ratios for contrasting elastic compaction with virgin compaction. Specific unit compaction is the compaction of deposits per unit of thickness per unit of increase in applied stress during a specified time period (Poland and others, 1972). The transition from elastic compaction to virgin compaction of aquifer materials may result in an order-of-magnitude increase in the measured amounts of specific unit compaction, aquifer compaction per unit of water-level decline, and land subsidence per unit of water-level decline (Riley, 1969; Meyer and Carr, 1979; Holzer, 1981).

The difference between aquifer compaction and land subsidence can be clarified by briefly describing how they are measured. Aquifer compaction is determined by measuring the distance between the land surface and the bottom of a well that may only partially penetrate the aquifer; compaction below the bottom of the well is unmeasured. Land subsidence is measured by resurveying land-surface points of established elevations; subsidence equals the amount of all compaction underlying a given point. Thus, a measurement of aquifer compaction will be less than a measurement of land subsidence for a given point and time unless the well in which it is measured fully penetrates all compressible deposits of the aquifer.

The rate and magnitude of aquifer compaction and land subsidence commonly vary considerably from place to place. Localized differential compaction and subsidence are sometimes accompanied by the formation of fissures and faults. Localized differential subsidence, fissures, and faults are most likely to occur near the edges of a basin where compaction may be greatly influenced by the depth and geometry of bedrock. Bedrock as defined in this report includes all rocks and deposits of the mountains and subsurface that are generally resistant to deformation related to ground-water withdrawal. Differential compaction of the aquifer in such places may cause the land surface to bend across prominent bedrock features; the accompanying tensile strain may result in fissuring. Subsidence fissures commonly overlie shallowly buried fault scarps or convex irregularities in the bedrock; those that form above buried fault scarps may show vertical offset (Feth, 1951; Schumann and Poland, 1970; Holzer and others, 1979; Jachens and Holzer, 1979). Some localized differential subsidence and fissures occur in the central parts of a basin where bedrock is deeply buried. Subsidence and fissures such as these probably are the result of differential compaction across abrupt lateral depositional features that affect the compressibility and (or) water-bearing characteristics of the aquifer.

Although land subsidence and earth fissures commonly result from compaction of the aquifer, they may result also from other processes. Land subsidence and fissures, for example, sometimes occur as a result of *hydrocompaction*, which is the vertical compaction or collapse of near-surface low-density sediments following a sudden or unusually large application of water to the land surface (Pashley, 1961; Poland and others, 1972; Davidson, 1973). Fissures also form in response to desiccation, which is the drying of near-surface fine-grained sediments by evapotranspiration (Neal and Motts, 1967). Desiccation of sediments may occur in the unsaturated zone or in the zone drained by shallow water-level declines (Anderson, 1978). Earth fissures have also been attributed to horizontal-seepage forces (Lofgren, 1971) and horizontal contraction caused by capillary stresses in the zone drained by water-level declines (Holzer and Davis, 1976; Holzer, 1977). Some fissures may be the result of natural compaction or seismic activity.

Some earth fissures appear to form near the land surface and deepen with time. Others may initially form at depth and propagate upward (Neal, 1972; Holzer, 1977). Fissures initially appear at the land surface as segmented arcuate to linear narrow cracks; segments typically form en echelon or polygonal patterns (Holzer, 1977). Fissures that accompany hydrocompaction and desiccation generally form arcuate to polygonal shapes that are tens to hundreds of feet across; fissure segments generally are tens of feet deep (Pashley, 1961; Neal and Motts, 1967; Anderson, 1978). Fissures that accompany water-level decline, aquifer compaction, and land subsidence generally form arcuate to linear en echelon patterns that are hundreds to thousands of feet in length; fissure segments may be hundreds of feet deep (Holzer and Davis, 1976; Holzer, 1977; Anderson, 1978).

Subsequent erosion and enlargement of earth fissures by flowing water result in the formation of fissure gullies; gullying is often dramatic following periods of heavy precipitation. Sediment that is eroded from near the land surface travels downward and is deposited at depth in fissure cavities (Holzer, 1977). Thus, the ultimate size of a fissure gully is dependent on the initial sediment-storage capacity of the underlying fissure. The sediment-storage capacity of fissures that accompany water-level decline, aquifer compaction, and land subsidence generally is large. Some resultant fissure gullies are more than 1,000 ft long and as much as 10 ft wide and 10 ft deep (Laney and others, 1978). Fissure gullies that result from hydrocompaction and desiccation, however, generally are small because the initial fissures are shallow and have limited sediment-storage capacity. Gullying may continue until earth fissures are filled completely with sediment. In arid environments, fissures may not fill for tens of years (Anderson, 1978). In areas of active land subsidence, new fissures may form from time to time and existing fissures may occasionally reopen; therefore, gullying may be a persistent problem.

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By

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